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EXECUTIVE SUMMARY

This report presents preliminary results from an effort to develop prototype N95 respirators in conjunction with various fabrication techniques including approaches that involve additive (i.e. 3D printing). During the project, N95 filtration media was supplied by Oak Ridge National Laboratory. Rapid prototyping of non-functional parts for qualitative evaluation of fit and assembly is a useful technique, and one that was readily implemented early in the project. However, a major aspect of N95 respirator development is testing and evaluation in conjunction with OSHA/NIOSH requirements. As a result, fabrication of functional components is a critical part of the development process. Due to limited material selection and a tendency toward high porosity and brittleness, direct implementation of 3D printed parts in N95 respirators is limited. However, as demonstrated by this project, 3D printing technologies can be effectively leveraged to create tooling which can be combined with other manufacturing processes to produce high-quality, functional N95 respirator components. Techniques included direct use of 3D printed molds for production of face seals from skin-safe silicone and mask shells from heat-resistant polyurethane, as well as the creation of vacuum form tooling for production of mask shells from ABS and HIPS. Preliminary testing of N95 mask prototypes was performed at NETL Morgantown in conjunction with ES&H, illustrating areas for improvement and highlighting the importance of face seal and mask shell geometry with respect to the user’s face. Additive manufacturing allowed rapid prototyping of functional components in a laboratory-scale environment, and through the creation of tooling rather than mask components directly, volume production is more readily enabled.
INTRODUCTION

Coronavirus Disease 2019 (COVID-19) is caused by a coronavirus called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The global pandemic is believed to have originated from Wuhan, in the People’s Republic of China, where the index case (patient zero) was first reported in 2019 [1]. By December 2020, over 70 million cases and 1.6 million deaths have been reported worldwide [2]. The Centers for Disease Control and Prevention (CDC) reported 216,025 deaths from COVID-19 as of October 15, 2020, but estimates 299,028 excess deaths to have occurred through October 3 relative to 2015-2019 [3]. Furthermore, new strains of COVID-19 are beginning to emerge, some with significantly greater transmissibility [4].

As of December 22, 2020, two vaccines have been given emergency use authorization in the U.S. [5]. However, the timeline for widespread vaccination is projected to be anywhere from late spring to fall 2021 [6]. In the meantime, there is a significant need for personal protective equipment (PPE). Most importantly are masks or respirators, as COVID-19 is transmitted primarily through respiratory droplets that are released when an infected person coughs, sneezes, or speaks [7]. For the average citizen, a simple cloth mask or surgical mask can be effective in slowing the community spread of COVID-19 and thus reduce the burden on healthcare systems and limit infection of vulnerable individuals [8].

However, front line workers, such as doctors, nurses, and first responders may desire more substantial protection due to the proximity and frequency of contact with infected persons. Here, the most common piece of PPE is the N95 mask or respirator [8,9]. The centerpiece of these masks is a filtration media capable of removing 95% of non-oily particles in the 0.3 μm size range [10]. In some applications, a further consideration is resistance to fluid penetration; these masks are termed surgical N95 masks.

Most common, is the melt-spun (or blown) N95 fabric, in which thin thermoplastic fibers (ex. polypropylene) are extruded and spun or blown into a randomly woven sheet [11]. While the interwoven nature of the N95 material provides some mechanical filtration, most critical to the filtration of small particles is the electrostatic or electrophoretic mechanism [11]. This fact makes N95 fabric particularly difficult to decontaminate without affecting filtration ability [11].

Domestic production of N95 respirators continues to fall short of demand due to uncertainty over profitability: retooling a production line to make N95 respirators is a costly proposition, and cheaper imports threaten a company’s ability to recoup its initial investment [12].

Initial discussions with local medical providers in both the Pittsburgh regional area and North Central West Virginia indicated that in the first several months once the virus was detected (in these areas), there was a shortage of adequate respiratory PPE. This resulted in a number of non-optimal approaches including emergency authorization of extended use and re-use of respiratory PPE. With regards to the N95 filter material previously referenced, this practice along with disinfection / cleaning practices could lead to reduction in the electrophoretic mechanism that is necessary for maintaining efficiency in trapping small particles such as viruses. In response to this shortage, numerous organizations and individuals from across the nation and around the world proposed the use of ad-hoc
breathing masks made from common household materials or fabricated through rapidly evolving technologies such as 3D printing.

Since its beginning in the 1980’s, 3D printing has transitioned from the university research laboratory to industry and is currently available to the residential hobbyist. While this has most surely enhanced creativity and supported budding entrepreneurial endeavors, it has challenged the ability to ensure the safety of products that may be used by the public. In particular, the multitude of “hobbyist” designed 3D printed mask being presented to the public and the medical community were not subject to the rigorous industrial standards used to verify the safety of commercially available respiratory PPE.

![Figure 1. Honeywell half-mask respirator (left, from Honeywell), 3M N95 particulate respirator (right, from 3M)](image)

There are generally two types of N95 respirators available on the market: those which implement replaceable filter cartridges, and those which are completely disposable. The former tend to be significantly more complex, costly and heavy, but may include more substantial face seal materials which enable a better fit on a variety of face shapes. The latter are typically soft masks comprised mainly of N95 material and may include simple neoprene face seals and/or check valves to allow reduced exhale effort. It should be noted that for frontline worker applications, it is paramount that any mask or respirator NOT include check valves to ensure protection not only for the user, but also for those around them.

Other than fit, the biggest difference between the two mask types is in how the N95 material must be processed or manipulated. The soft mask, while being very simple and lightweight, requires additional N95 processing and potentially, additional raw material, which has been in short supply. The half-mask on the other hand, with its replaceable filters, could be more amenable to a modular approach in which raw N95 sheets could be easily replaced and the remaining portions of the mask disinfected in an autoclave, etc. This could result in greater re-use of PPE, while ensuring new filter media can be utilized each time.

A prototype N95 mask was developed over the course of this effort which has a similar design to the half-mask respirator, but which accepts raw N95 fabric as filter media. Furthermore, the design was developed to be as simple and lightweight as possible, amenable to numerous manufacturing techniques (ex. vacuum forming, injection molding).
During development, additive manufacturing was leveraged to produce non-functional prototype parts, functional parts, and tooling which can be implemented in secondary manufacturing processes. Using this approach, function components were rapidly produced and iterated, in conjunction with feedback from qualitative and quantitative testing and OSHA/NIOSH standards.

2 MATERIALS AND METHODS

While there are a number of 3D printable mask/respirator designs available on the internet, quality and trustworthiness are largely unknown. As previously noted, numerous respiratory PPE designs were provided as open-source designs by both the hobbyist (concerned citizen) as well as professional organizations. Examples include the community lead effort known as the “Maker Mask” project [13] to solutions provided by 3D printing industry leaders such as 3D Systems [14]. In response to the multitude of PPE being presented to the general public and the medical community, the National Institute of Health (NIH) working in conjunction with the America Makes established the COVID 3D Trust as part of the NIH 3D Print Exchange [15].

One of the largest benefits of this project, and the national lab effort in general, is the credibility and trustworthiness it brings to any resulting R&D product. This is an inherent result of the experience and expertise of the DOE national lab system, as well as the resources and capabilities of individual labs and projects. The National Energy Technology Laboratory (NETL) brings capabilities and expertise in 3D printing from past work developing functional components using FDM and polyjet printer technologies for various thermal science applications. In this regard, multiple 3D printer capabilities were utilized, at both the NETL Morgantown (Stratasys Objet Eden 260 and MakerGear M2) and Pittsburgh sites (Stratasys F120 and F170), to create parts and tooling needed to develop prototype N95 respirator prototypes. This represents a doubling of 3D printing capabilities at the NETL Pittsburgh site and was critical to the success of the project.

2.1 ORNL DESIGN

At the beginning of the project, as NETL researchers began their involvement with the larger national lab group dealing with masks/respirators and other COVID-19 consumables, colleagues at Oak Ridge National Laboratory (ORNL) shared a preliminary 3D-printable respirator design. The design consists of a hard outer shell, with strap hooks, a flexible rubber face seal, a...
filter media retaining ring, and a filter cover. Figure 2 shows an initial test print of all components in acrylonitrile butadiene styrene (ABS) plastic, using the Stratasys F170 FDM printer at NETL Pittsburgh. However, as dictated by the design, the component in the upper left corner of the photo must be created from a soft material in order to effectively seal to the user’s face. To accomplish this, a number of high-quality two-part curable materials were purchased from Smooth-On, a company specializing in a variety of low-volatility rubbers and plastics.

- Platinum-cure EcoFlex 00-35 silicone rubber was purchased for creating face seals, as it is has good long-term stability, is certified skin-safe, and has a rapid cure time of ~10 minutes.
- Task 8 heat resistant polyurethane resin was purchased to allow high-quality plastic mask components to be produced which can be effectively disinfected in an autoclave, etc. up to 263 °F.
- The Smooth Cast 65D semi-rigid urethane casting resin was purchased to allow mold forms to be created from 3D printed parts.

Additional items included Monster Clay® for sealing and supporting molds, Universal Mold Release spray to aid in removal of cast parts, Xtend-It dry gas blanket for extending the life of opened urethane resins, Silc Pig silicone pigment to add color to silicone parts, and So Strong urethane pigment to add color to heat resistant polyurethane parts. Part creation using any of the above materials required no specialized ventilation or PPE, other than standard safety glasses and nitrile/latex/vinyl gloves. Initially, the 3D printed ABS plastic face seal shown in the upper left of Fig. 2 was used to create a mold from Smooth Cast 65D. Due to the shape, a two-piece mold design was necessary, proving challenging to create while maintaining desired part dimensions and tolerances. In particular, part removal was significantly hindered by the small ridges which help to provide a positive seal between the N95 fabric and filter cap. The two-piece mold can be seen in Fig. 3.

![Figure 3. Two-piece mold (Smooth Cast 65D) for creating silicone face seals](image)
EcoFlex 00-35 silicone rubber was poured into the lower mold cavity and the upper part was slowly inserted, pushing extra material out through runners created at the high points. While the resulting part reasonably matched the original 3D printed plastic component, the dimensional tolerances and edge quality were poor. As a result, re-assembly of the mask was difficult. To gain improved control of cast part tolerances, creation of the two-piece mold via 3D printing was tested. It was initially unclear if adequate tolerances could be achieved, if molded parts could be easily removed, and/or if the porosity of molds created via FDM would cause issues (i.e. leakage).

The CAD file for the face seal provided by ORNL was imported into AutoCAD Inventor to create the mold. The lower mold was created first, by extruding the face seal geometry through a solid block, creating a negative cavity. Next, an assembly was created between this lower mold cavity and the original face seal geometry, which was subsequently subtracted from another block to create the upper mold. Afterward, unwanted material was removed from the upper and lower molds to create “1/8-1/4” thick shells, thus minimizing print time and material usage. A lip was added to each mold half to aid in separation after curing. Finally, holes were added at high points to allow excess material to flow out and to eliminate air bubbles. The final mold can be seen in Fig. 4.

![Figure 4. 3D printed two-piece mold for ORNL face seal](image)

Only a small amount of hand finishing was needed between the upper and lower halves of the mold to remove rough edges in order for them to fit together, even with exact-fit dimensions within the CAD models. This resulted in an extremely precise mold. Using the mold in Fig. 4, silicone face seals were created from the EcoFlex 00-35 rubber. This time, the resulting part dimensions exactly matched the 3D printed plastic part and a significant improvement in edge quality was achieved. Additionally, the 3D printed molds exhibited no issue with part removal or porosity (mold release spray was still used to minimize sticking). However, the tight seal created between the plastic mold and rubber part required significant force to separate by hand, an issue that will be addressed below.
Figure 5. Final mask assembly, preliminary ORNL design

Figure 5 shows the final assembled ORNL respirator (left), along with a detail image showing the face seal and filter retaining ring assembly, without N95 media and filter cap (right). While the manufacturing approach developed during this initial prototyping phase was highly successful, it was immediately clear that the mask design had significant flaws, a finding that was echoed by ORNL as a result of testing performed by Sandia National Laboratory. As such, ORNL moved on to other designs, as did NETL, taking note of areas for improvement. These are as follows:

1. The face seal shape and thickness were not sufficient to provide positive fit on a wide variety of face shapes
2. The filter area was too low to meet NIOSH/OSHA pressure drop requirements (to be discussed in detail below)
3. Mask assembly and replacement of N95 fabric was difficult and prone to damaging the filter media

NETL researchers began the task of developing a new respirator design which addresses these shortcomings and leverages the manufacturing and materials knowledge developed during this initial phase.

The major goals of this new design were

1. A simple and lightweight design, which could be easily and cheaply manufactured using a variety of methods.
2. The ability to accommodate various face shapes and sizes using a combination of seal and mask shell geometric variations.
3. A modular approach, in which portions of the respirator are common among sizes/shapes and for which most components can be sterilized and re-used.
4. The ability to accommodate standard and non-standard/raw N95 filter media.

Upon fabrication, each new respirator design would be subject to the Occupational Safety and Health Administration (OSHA) Quantitative Fit Test Procedure [16] to determine its effectiveness at preventing the inhalation of particulate matter greater than or equal to 0.015 micron. These tests were performed using a TSI PortaCount Pro 8030 (Fig. 6) which was
operated by trained ES&H staff at the NETL Morgantown campus.

Tests performed using the TSI Portacount 8038 were processed by the TSI FitPro+ v3 Test Software which automates the calculation of Fit Factors over the course of eight activities including: Normal Breathing, Deep Breathing, Head Side to Side, Head Up and Down, Talking, Grimace, Bending Over and Normal Breathing. The Fit Factors for each exercise are calculated by comparing the particle concentration in the ambient environment to that of the gas extracted from the respirator while worn by a user. The details of this calculation are provided in the Portacount 8038 User Manual [17]. A higher Fit Factor suggests a more efficient respirator, with a score of “100” considered a passing level.

3 RESULTS AND DISCUSSION

In accordance with the major design goals above, the framework for a modular mask prototype was established, including the following key components.

1. Face seal: the fundamental contact point between the user and the mask and a critical aspect of achieving a positive fit factor in NIOSH/OSHA testing. Expected to be produced from a skin-safe rubber, Smooth-On EcoFlex 00-35 during this prototyping phase.

2. Mask shell: the underlying structure of the mask, which includes a contoured shape for ideal engagement with a variety of face shapes and synergistically integrates with the face seal to enable high fit factor. Must include attachment point(s) for modular, removable filter cartridges and could include integrated or modular strap hooks.

3. Filter cartridge(s): modular/removable filter holder which enables non-standard raw N95 fabric to be easily replaced and/or enables adapters to be developed for use with existing filter cartridges (ex. 3M, Honeywell). Design must include filter cover to limit potential filter media fluid contamination.

Over the course of the project, a number of design revisions were made. This began with a pre-prototype, which allowed CAD workflows to be established and fabrication techniques refined, relative to those employed during creation of the ORNL mask. Later, two viable prototypes were developed and evaluated in accordance with NIOSH/OSHA quantitative testing. Feedback from testing was used to make design improvements and/or recommendations.

The design process began with a representative three-dimensional head geometry. In the absence of 3D scanning capabilities at NETL, CAD geometries published by NIOSH [18] were used as a basis for mask development. Generated for respirator fit purposes, geometries included small, short-wide, medium, tall-narrow, and face shapes. Prototyping at NETL
primarily utilized the tall-narrow geometry due to researcher fit compatibility. However, an identical procedure can be performed for any of the other geometries, or custom shapes created as a result of 3D scanning.

![Diagram of mask shell and face seal design process]

**Figure 7.** Mask shell and face seal design process diagram

A mask design methodology was developed, allowing various aspects of the geometry to be modified and re-generated as design revisions were made. This process is outlined visually in Fig. 7. First, three-dimensional curves were generated by projecting a desired 2D mask profile onto the corresponding NIH face geometry. The face seal was created first by sweeping desired cross-sections along the projected curve. The design of the face seal was such that it included a concave pocket, to allow it to be stretched over the perimeter of the mask shell. Next, the mask shell rim was created using a similar sweep operation, using the face seal pocket as a basis for the geometry. This resulted in creation of the mask shell rim which exactly matches the geometry of the face pocket. Using this approach, the two pieces fit together tightly without the need for adhesives. This feature allows complete disassembly of the mask for disinfecting and/or exchanging pieces to optimize fit. Filter ports were located in three-dimensional space relative to facial features of the NIH head geometry and the mask rim geometry. Finally, a shell body was created which connects the rim and filter ports, completing the mask shell.
3.1 Pre-Prototype Designs (Rev0)

An initial pre-prototype design (Rev0) was developed using the methodology above, shown in Fig. 8. One complaint of the original ORNL design was weight and bulk. As a result, design Rev0 was a small and tight-fitting shell. The mask rim which interfaces with the shell was nearly vertical, with a small concave pocket to retain the face seal. The mask was 3.2 mm thick, with the rim being slightly thicker to provide adequate structure for a tight-fitting face seal. Some aspects of this early design were constrained by difficulties in CAD operations, such as sweeping and extruding. Over subsequent revisions, many of these difficulties were overcome, allowing more deliberate and refined designs to be developed. Filter attachment points were placed far apart to accommodate high filter area. The filter ports consisted of a tapered 3.2 mm thick flange, designed to mate with a similarly tapered filter tray stem.

Design Rev0 was 3D printed from ABS plastic at NETL Pittsburgh using a Stratasys F170 printer. It was created with complete fill, to minimize porosity. Standard support settings were utilized, and support removal was accomplished using ~4 hr soak in EcoWorks cleaning agent. Afterwards, the parts were dried overnight to ensure evaporation of any liquid trapped within the porous matrix. The printed mask can be seen in Fig. 9. Overall, build quality and structural rigidity were very good. The shell exhibited no visibly porous regions, which can occur with thin, unsupported structures.

Using the same approach taken during fabrication of the ORNL respirator design, a two-piece mold was designed to create a skin-safe silicone face seal from Smooth-On EcoFlex 00-35. Because of significantly greater geometric complexity in the new seal designs, mold design was similarly more involved. A number of considerations were required in the design of face seals intended to be molded from silicone. First, square edges were favored over rounded to eliminate creation of very thin, protruding edges where the top and bottom parts of the mold meet. Most importantly, all vertical surfaces were created with a slight inward taper, to ensure easy part removal. These aspects were not considered for the concave pocket, which by design includes overhung geometry which would preclude removal of a rigid part. However, the EcoFlex silicone is highly pliable, making careful removal possible. In all cases, parts created using this methodology included liberal use of mold release spray.
The mold was printed using the same Stratasys F170 printer as the mask shell. After support removal, a small amount of hand finishing of the mating surfaces was required. The design of each mold half included exact mating dimensions, without consideration for print tolerances. The printed two-piece mold can be seen in Fig. 10 (left), along with the molded face seal installed on the mask shell from Fig. 9. It can be seen that the mold design includes a number of locations for captive nuts and bolts, so that the mold pieces may be separated more easily. This addition was a result of significant difficulty in separating ORNL design face seal mold by hand. Here, bolts are unthreaded completely as the mold is assembled with liquid silicone in the cavity. After curing, the bolts are driven in, alternating in a ‘cross’ pattern, slowly separating the mold halves.

Over the course of the project, mold design methodologies were refined to minimize material usage and print times via utilization of shelled geometries which are significantly more complex to design in CAD software. On average, the two-piece molds took ~12-18 hrs to print on a Stratasys F170 (or F120) printer, placing both halves on a single print try. Later in the project, these print times were reduced to ~8 hrs by optimizing CAD geometries. Printed mask shells took on average ~4 hrs to build on the same printers.

The primary focus of design Rev 0 was with regards to the face seal and shell. However, some early development of the filter trays occurred, in particular the mating interface. A number of prototype interfaces were designed and printed, to test engagement, removal, and durability.

3.2 NETL DESIGN (REV1)

Using what was learned during pre-prototype development, improved respirator designs were created. Up until now, no formal quantitative testing had been conducted, however qualitative fit testing was used to evaluate comfort and seal integrity. A revised mask shell design (Rev 1.0) can be seen in Fig. 11. A major issue with the pre-prototype designs (both Rev 0 and the ORNL design) was a thin face seal which does not sufficiently conform to the user’s face. This is contrary to most commercial respirators from 3M and Honeywell, which include a large, curled lip that can deform around the face. To address this, a revised face seal was designed, which was substantially thicker between the mask shell and face, and
extended further into the mask cavity. Additionally, after designing the seal at mask scale, it was shrunk by 10% before creation of the two-part mold. This resulted in a seal that had to be stretched over the mask, ensuring a tight fit.

Next, the near vertical lip and small concavity of Rev 0.1 (see Fig. 8) was not sufficient to hold the face seal tightly, in particular around the nose and chin. As a result, the entire lip was redesigned so that it extended outward rather than toward the user’s face. Finally, tabs were included around the perimeter of the mask to enable nylon webbing to be used strap material. Here, the intent was that the tabs protrude through the perimeter of the face seal, providing further anchoring. Placement of the filter holders was also altered slightly, to provide a smoother transition from the rim to the mounting face. In Rev 1.1, design of the filter hold interface included a tab, which locates the filter at a particular angle and prevents rotation. This was later determined to be unnecessary and the sharp corners were likely to leak.

The revised mask design was again printed from ABS using the Stratasys F170 printer, with identical build settings to Rev 0. The printed mask, along with several prototype filter connections can be seen in Fig. 12 (left). During development, the approach of printing small subsections of interlocking parts to evaluate clearance and fitment was often used. This allowed multiple part tolerances to be considered at once, leading to rapid optimization of geometry with minimal waste. The two-piece mold for the revised face seal can be seen on the right in Fig. 12. To ensure the tabs shown Fig. 11 are able to easily and consistently protrude through the molded face seals, small tabs were included in the upper part of the face seal mold, which extend approximately halfway through the seal. These tabs ensured that the molded parts had clear indication of where the strap hook tabs should protrude through the seal, allowing slots to be easily cut by hand.

![Figure 11. NETL mask shell design, Rev 1.0](image)

![Figure 12. 3D printed mask shell, Rev 1.0 (left), including prototype filter connection interfaces, 3D printed two-piece mold (right)](image)
Development of the filter trays and a suitable click-connect interface was also a significant part of Rev 1.1. As discussed above, the tabbed interface shown in Fig. 11 and Fig. 12 (left) was abandoned after testing a number of different connection geometries.

A simple connection interface was developed which included a 50 mm flat face on the mask, with a 35 mm diameter, 5 degree inward tapered hole. The filter connection included an identical taper and two 135-degree wide tabs. This width prevented the filter holder from wobbling, but still allowed sufficient deformation that the holder could be removed by pinching the tabs from the inside of the mask. The tabs included 0.5 mm overhang, which allowed a strong, but removable, connection. The tabbed connection can be seen on the right in Fig. 13. The filter holder, shown on the left of Fig. 13, consisted of a simple circular tray, with an outer ledge that allows filter media to be tightly sealed between it and an accompanying cap. In design Rev 1.1 the interface between the cap and the filter tray was threaded, however this configuration was later abandoned for a more robust design.

![Figure 13. Assembled 3D printed mask, Rev 1.0 (left), showing filter connector detail (right)](image)

When designing the filter holder, a major consideration was filter area. In NIOSH certification testing for non-powered respirators, a < 1 in H₂O pressure drop is required for an air flow rate of 85 L/min [19]. In a practical sense, this requirement translates a level of breathability for the person wearing the respirator. From a design perspective, this is largely dictated by the area of the N95 filter media being utilized and may vary between manufacturers. During this project, all N95 media was supplied by ORNL, and was a melt-spun fabric. ORNL specified that three-layers were required to meet the applicable N95 filtration efficiency. Results from pressure drop testing at SNL were relayed to the national lab mask/respirator working group, indicating a total required filter area of ~20 in². This was loosely confirmed at NETL through measurements in a simplified test fixture, which indicated an equivalent open area of the 3-layer filtration media of ~0.6%.

Using this information, 3.5-inch and 4-inch round filter trays were designed, corresponding to ~19 in² and 24 in² total filter area per pair, respectively. The estimate of equivalent open area of the filtration media guided the dimensions of the filter tray and connector. In all
instances, it was ensured that the filter media would be the most restrictive part of the air flow path (i.e. no mask components would further impede the flow of air).

A final consideration was with regard to processing of the filter media ahead of installation within the filter holder. During fabrication of the ORNL mask design, and in early versions of Rev 1.0, the filter media was cut by hand. For the ORNL design, because the filter cloth was pulled around the retaining ring, a clean cut was not critical. However, the NETL filter holder design is such that the media must be tightly sandwiched between the tray and cap. This results in a simple re-assembly process and potentially less material usage/waste, however, requires a carefully cut edge. To facilitate this, N95 fabric was cut using a GrandeMark die-cutting machine, with custom cut dies (3.5 inch and 4 inch diameter). Furthermore, it was found that if (3) layers of N95 were stacked ahead of cutting, the cutting process tended to close the edges such that the individual layers remained together. The cutting machine and an example of the cut 4-inch diameter 3-layer N95 media can be seen in Fig. 14.

![Pattern cutting machine and example (2x) 4-inch diameter 3-layer N95 media](image)

**Figure 14.** Pattern cutting machine and example (2x) 4-inch diameter 3-layer N95 media

The fully assembled Rev 1.0 prototype respirator can be seen in Fig. 15. Here, all hard components were 3D printed, and the filter caps only served as retaining rings, providing no splash protection. The molded silicone face seal can be seen in the image on the right, extending into the mask cavity to provide adequate sealing against a variety of face shapes/types. Nylon webbing was used as strap material, attached to tabs which protrude through the perimeter of the face seal.
Figure 15. NETL Respirator Rev 1.0, including 3D printed plastic and molded silicone parts, ORNL-supplied N95 media, and 4-inch diameter filter cartridges.

Qualitative fit testing showed that a good seal can be maintained for some face shapes (i.e. tall/narrow). The interface between the filter holders and mask shell provided an excellent seal, along with the ability to rotate and/or remove the filter trays as needed. It should be noted that for FDM 3D printed parts, the durability of these types of deformable interfaces is not equivalent to commercially manufactured plastics, as was expected.

In general, the mask shown in Fig. 15 provided good fit and function, however several aspects required revision (Rev 1.1). First, the approach of using a threaded filter cap was quickly abandoned due to an inability to maintain adequate pressure on the edge of the filter media, as well as rotation of the ring during installation potentially tearing the media. Instead, a tabbed design similar to that used to attach the filter trays to the mask shell was used. A number of design iterations were considered, before settling on (4) tabs, with ~0.5 mm overhang and a tapered profile to allow easy installation. The tabs were non-uniformly spaced, to create clearance where the filter cartridge will be in close proximity to the mask shell.

Figure 16. NETL Filter Cartridge, Rev 1.1, including splash shield and tabbed interface.

The revised design, printed on the Stratasys F120 printer, can be seen in Fig. 16. An addition
which is immediately apparent is a splash shield, with air passages located on the side. During N95 media installation, the air holes can be located where they will be least likely to see splash contamination. Furthermore, the entire filter cartridge, once installed on the mask, can be rotated at any angle desired by the user. Build times for a pair of filters was ~ 2 hrs. Afterwards, soaking in EcoWorks solution was required to remove support material (ex. within cap holes or underneath tab edges). The part thickness, flat geometry, and build settings which included complete fill, resulted in the porosity of the filter cartridges being of little concern for prototyping purposes.

However, this was not so for the mask shells, which exhibited visible porosity. This is partially a result of the desired ~2 mm shell thickness, as well as the largely unsupported nature of the build geometry. As a result, alternative techniques were considered to develop non-porous mask shells from Task 8 heat resistant polyurethane. Utilization of this material allows components to be sterilized in an autoclave, or dishwasher, as well as being amenable to an identical molding procedure as the silicone used to create face seals.

![Figure 17. NETL mask shell design, Rev 1.1](image)

However, a number of minor design modifications were required to ensure the mask shell was amenable to the molding procedure. These changes were more critical here compared to the silicone due to the rigid nature of the final parts and the potential for difficulties in de-molding. First, it was ensured that all surfaces of the mask shell included a slight inward angle, with no overhanging features. This required a slight repositioning of the filter ports, placing them closer together. Additionally, the mask lip profile was further angled outward, to eliminate any overhang adjacent to the filter port locations. The revised mask shell can be seen in Fig. 17, in comparison to the one shown in Fig. 11. Due to perceived difficulties in mold design and de-molding, the filter tabs shown in Fig. 17 were eliminated when designing the two-piece mold. As will be discussed below, an alternative strap attachment mechanism was developed.
Using a similar approach to molds for the silicone face seals, the revised mask shell was converted to a two-piece 3D printable mold. The final mold, printed on a Stratasys F170 printer, can be seen in Fig. 18. Similar to the silicone molds, captive nuts and bolts were included to facilitate easy separation of the mold pieces after curing. The mold was used in conjunction with Smooth-On Task 8 heat-resistant polyurethane resin to create a non-porous mold shell capable of being disinfected at high temperature. Additionally, Smooth-On So-Strong pigment (blue) was added to the two-part polyurethane resin mixture and Silc-Pig pigment (black) was added to the two-part silicone mixture, for aesthetic purposes. The final mask can be seen in Fig. 19. Here, the molded mask shell is an identical copy of the CAD model shown in Fig. 17, minus the strap hook tabs. The same contoured face seal can be seen in Fig. 19 (middle), as well as the fact that the tabbed filter trays fit identically to that of the 3D printed mask shell. Finally, a revised strap hook design can be seen in Fig. 17 (right), which simply connect between the shell and filter tray. This design resembles that of the Honeywell mask shown in Fig. 1.

**Figure 18.** 3D printed two-piece mold of NETL mask shell design, Rev 1.1

**Figure 19.** Final NETL mask prototype, Rev 1.1
Rev 1.1 Testing

As previously noted, testing of the respirators was conducted according to the Quantitative Fit Test Procedure, OSHA 1910.134 using a TSI Portacount Pro 8030 maintained by the NETL ES&H staff at the Morgantown campus. The test procedure required a plastic tube connected between the Portacount machine and the respirator (Fig. 20, left). For testing commercially available respirators, a specially prepared sampling adapter that is available from the Portacount machine manufacturer is often used to connect the tubing to the respirator. The test procedure also permits the use of “homemade adapters”, which was the option chosen for testing the NETL REV1.1 mask (Fig. 20, right). This option was selected to maintain the integrity of the actual mask. However, the crudeness of the adapter may have contributed to the inability of the REV1.1 respirator to pass the quantitative fit test.

![Figure 20. PortaCount quantitative testing of Rev 1.1 at NETL MGN](image)

The Quantitative Fit Test compares the concentration of microscopic particulates (>= 0.015um) outside of the respirator to the concentration of particles that have leaked into the respirator. Individual “Fit Factors” are calculated by taking a ratio of Outside to Inside particle concentrations while the wearer performs eight different activities. A passing Fit Factor of greater than or equal to 100 indicates that the air inside the respirator is 100 times less containment as the air outside. To ensure an adequate supply of submicron particles in the ambient air, the Portacount Pro Respirator Fit Tester generates the necessary particles from isopropyl alcohol. See the Portacount Pro Respirator Fit Tester manual for more details on the testing procedure and fit factor determination [17]. For comparison, a 3M N95 disposable mask was also tested (Fig. 21). Detailed results from both

![Figure 21. 3M 9211 “control” mask, connected to Portacount](image)
the “NETL Blue Printed” (NETL Rev 1.1) respirator and the 3M 9211 (N95) mask are provided in Appendix A.

Testing found that the NETL Blue respirator REV 1.1 failed all of the fit test exercises. This was not particularly surprising as the NETL mask would be considered a prototype. Results from the eight exercises that constitute the Fit Test are given in Table 1 for the NETL Rev 1.1 mask and Table 2 for the 3M N95 (pass score >= 100).

### Table 1: Results from Respirator Fit Test for NETL Rev 1.1 Respirator

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Fit Factor</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Breathing</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Deep Breathing</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Side to Side</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Up and Down</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Talking</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Grimace</td>
<td>Excluded</td>
<td></td>
</tr>
<tr>
<td>Bending Over</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td>Normal Breathing</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td><strong>OVERALL FF</strong></td>
<td><strong>3</strong></td>
<td><strong>N</strong></td>
</tr>
</tbody>
</table>

### Table 2: Results from Respirator Fit Test for 3M N95 Respirator

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Fit Factor</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Breathing</td>
<td>200+</td>
<td>Y</td>
</tr>
<tr>
<td>Deep Breathing</td>
<td>200+</td>
<td>Y</td>
</tr>
<tr>
<td>Head Side to Side</td>
<td>200+</td>
<td>Y</td>
</tr>
<tr>
<td>Head Up and Down</td>
<td>200+</td>
<td>Y</td>
</tr>
<tr>
<td>Talking</td>
<td>200+</td>
<td>Y</td>
</tr>
<tr>
<td>Grimace</td>
<td>Excluded</td>
<td></td>
</tr>
<tr>
<td>Bending Over</td>
<td>33</td>
<td>N</td>
</tr>
<tr>
<td>Normal Breathing</td>
<td>43</td>
<td>N</td>
</tr>
<tr>
<td><strong>OVERALL FF</strong></td>
<td><strong>90</strong></td>
<td><strong>N</strong></td>
</tr>
</tbody>
</table>

There were a number of observed factors that most likely contributed to the failing score of the NETL Rev 1.1 mask. First as previously noted, the “Homemade” Hose Adapter was poorly designed for the test. The NETL Rev 1.1 respirator consists of two individual filter holder assemblies. A typical Fit Test would require that both filter holding assembly be present on the mask with the hose adapter permitting sampling of the gas on the inside of the respirator. An example of a commercially available adaptor for an MSA half-face respirator, similar in design to the NETL Rev 1.1 respirator is shown in Fig. 22. An alternative approach that is permitted by the OSHA Fit Test is to have a “Fit Test” respirator in which the hose connects to a port directly on the respirator itself. This was the option used for testing the NETL Rev 2 respirator.

In addition to the complications with the adapter, the actual fit of the NETL Rev 1.1 respirator was not optimal. The fit over the top of the nose and under the chin produced a noticeable
gap in the seal. This was in part due to a difference in the shape of the tall-narrow geometry of the NIOSH anthropometric headform CAD and the actual head shape of the tester. The issue of fit was further exacerbated by the rigidity of the mask itself. While the edge seal around the perimeter of the mask was flexible, the stiffness of the mask prevented it from taking the shape of the wearer. This could be overcome by a thicker flexible perimeter seal.

It is important to recall that Rev 1.1 and future Rev 3+ designs are all prototypes intended to provide insight into the respirator design process and how 3D printing may be leveraged in such endeavors. The inability of the NETL Rev 1.1 respirator to successfully pass the OSHA Fit Factor Test highlights concerns over the adequacy of community designed respirators that often undergo no testing before being made available to the general public. Use of a community designed respirator without proper testing could give the user a false sense of security leading to the user experiencing an undesired exposure.

Table 2 provides the results from the comparison test of the commercially available 3M N95 mask. As expected, this mask performed considerably better than the NETL Rev 1.1 design with scores of over 200+ for a majority of the exercises performed as part of the OSHA Fit Factor Test. However, the inability of this commercially certified mask to pass the Fit Factor Test after the “Bending Over” exercise demonstrates the difficulty in designing a mask/respirator that would protect the user under most activities. A shift in the position of the mask upon bending over most likely resulted in the overall failure during the final two phases of the Fit Factor Test, but additional testing would be required to ensure this effect.

A rigorous experimental study of both respirators would have included multiple tests of each, but time constraints limited the study to a single test of each mask design.

### 3.3 NETL DESIGN (REV2)

As a result of quantitative OSHA testing of design Rev 1.1, further revisions were identified for a second prototype. Furthermore, a major emphasis of the NETL effort has been R&D focused on leveraging 3D printing as a means to enable efficient secondary manufacturing methods. Manufacturing methods of interest were primarily those accessible at a lab or university scale rather than commercial techniques such as high-pressure injection molding. Discussed in section 3.2, this led to utilization of silicone and polyurethane molded part development; however, another technique of interest was vacuum forming.

Vacuum forming is often used to create thin shelled parts from a variety of thermoformable plastics. As such, it was believed to be well suited to efficient creation of mask shells. Compared to techniques such as high-pressure injection molding, vacuum form tooling and equipment is significantly less costly, making it well suited to smaller scale manufacturing. A Formech 450DT desktop scale vacuum former was purchased as part of the project.
vacuum former can utilize a variety of materials, in thicknesses up to ~5 mm. Currently, 1 mm and 1.5 mm thick ABS and high impact polystyrene (HIPS) were utilized in the work.

Examining the mask design (Rev 1.1) in section 3.2, the use of a thinner shell material required several aspects to be modified. Most critical, was the filter attachment point. A major challenge in the creation of vacuum formed parts is the trimming process. In the absence of automated cutting machines, achieving precise cut lines can be difficult. As a result, achieving perfectly round filter hole cutouts, capable of sealing tightly against the tabbed filter interface, was unlikely. Furthermore, due to the thinner material a tapered hole was not achievable by cutting, again compromising sealing ability.

An alternative configuration was developed, in which the filter interface was directly formed via a tapered inward cavity with a very slight overhang. The development of this interface involved a number of iterations, in order to achieve a compromise between good filter attachment and a design which allows easy de-molding, which is significantly hindered (or even prohibited) by concave or overhung geometric features. To simplify this process, a modular vacuum form was designed which includes removable ‘pucks’ containing the filter attachment geometry. The vacuum form mold, showing one installed ‘puck’ on the right side, can be seen in Fig. 23 (left) after printing on a Stratasys F120 printer. These mold forms took on average ~8 hr. to print and required no solution-based support removal.

The filter attachment geometry for vacuum formed shells included a 5 mm deep tapered section, identical to the angle of the filter tray stem. Below this, a slight 0.5 mm overhang is created to provide a flat surface or engagement of the filter tray stem tabs. This approach ensures that the trimming process does not have any impact on the filter tray seal. After de-molding, any trimming is purely cosmetic, to remove material protruding into the mask cavity. A second modification to the mask shell design was with regard to the exterior edge. For the thicker printed or molded shells, sufficient rigidity was achieved by the inherent shell thickness. However, the thinner vacuum formed materials required additional rigidity to ensure the tight-fitting face seal does not deform the shell. This was accomplished by designing a curled lip, providing inherent rigidity due to the three-dimensional nature of the geometry.
While Resign Rev 1 had reasonably good face seal anchoring, the shell lip geometry was further improved in Rev. 2. As seen in Fig. 18, greater concavity was created adjacent to the curled lip at the edge of the shell to provide greater hold on the face seal. This was accompanied by a slightly revised face seal geometry which adds material to take advantage of this concavity. Finally, the vacuum form mold included an integrated cut line around the perimeter, which allowed the shells to be trimmed by hand with reasonable ease. An example vacuum formed shell can be seen in Fig. 18 (right). The de-molding process includes pulling the shell from the mold, with the two filter ‘pucks’ installed. The interior of the pucks is cut by hand, and each ‘puck’ is pushed toward the interior of the mask.

Additional revisions to the face seal geometry were made in accordance with testing results from Rev 1.1. The largest sealing issues were identified near the nose and chin. Examining commercial mask offerings, these regions often include large pockets which eliminate any potential gaps. As such, three-dimensional pocket geometries were added to the face seal by connecting the left and right edges and smoothly filling the interior volume, blending into the existing surfaces. The final Rev 2 mask design can be seen in Fig. 24 (left). The same filter holders from Rev 1 are utilized, consisting of 3-layer N95 fabric and 3.5-inch or 4-inch diameters. In Fig. 24, black masks are 1.5 mm thick ABS and the yellow mask is 1 mm HIPS. On the right of Fig. 24, the improved face seal geometry can be seen, with greater chin and nose coverage. The tidy filter connections afforded by the tapered and overhung mold design are shown. Not pictured, the Rev 2 mask design utilized a similar modular strap geometry as Rev 1, however the angle and placement of the strap hooks was revised to improve holding ability. Additionally, the strap hooks interface with the protruding filter ports of the mask rather than the filter tray, ensuring leakage cannot occur due to bending of the filter cartridges.

**Rev 2 Testing**

Testing of the 1.5 mm thick ABS NETL Rev2 respirator was conducted at the end of January 2021. As noted above, this half-mask design incorporated several modifications to improve its filtration capacity. Unlike the testing of the Rev 1.1 mask, the Rev2 mask was modified to
include a penetration for the Portacount machine hose connection (Fig. 25). The penetration was created by drilling a 5/32-inch hole through the mask, inserting a hose adapter and sealing the adapter into place to prevent leakage. This results in a Fit Factor adapted respirator similar to commercially available masks that have a permanent hose adapter for testing and are only intended to be used for testing purposes.

The Quantitative OSHA Fit Factor Test was performed as previously done in accordance with the OSHA 1910.134 requirements. The results from this test are summarized in Table 3, with detailed found in Appendix A. While there were some improvements from the Rev 1.1 test, overall, the respirator was still not able to successfully pass the Fit Factor Test. Again, only a single test was performed which increases the associated uncertainties.

Similar to the Rev1.1 respirator, the Rev2 version did not provide a comprehensive seal around the bridge of the tester’s nose. When combined with the rigidity of the mask, even the flexible perimeter seal could not adequately eliminate all of the gaps. Again, this is most likely due to the differences in shape between the NIOSH anthropometric headform of the CAD model used to design the mask and that of the tester. This highlights the importance of shape in providing seals in rigid masks that are often observed in the community driven, 3D printed mask designs. Further revisions may address these potential leak points by providing a thicker perimeter seal around the sides of the nose or selecting a different anthropometric headform for geometry development.

![Figure 25. NETL Rev2 half-mask modified to include permeant inclusion of hose adapter for OSHA Fit Factor Testing.](image)

Table 3: Results from Respirator Fit Test for NETL Rev2 Respirator

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Fit Factor</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Breathing</td>
<td>5</td>
<td>N</td>
</tr>
<tr>
<td>Deep Breathing</td>
<td>4</td>
<td>N</td>
</tr>
<tr>
<td>Head Side to Side</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Up and Down</td>
<td>6</td>
<td>N</td>
</tr>
<tr>
<td>Talking</td>
<td>6</td>
<td>N</td>
</tr>
<tr>
<td>Grimace</td>
<td>Excluded</td>
<td></td>
</tr>
<tr>
<td>Bending Over</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td>Normal Breathing</td>
<td>22</td>
<td>N</td>
</tr>
<tr>
<td><strong>OVERALL FF</strong></td>
<td><strong>4</strong></td>
<td><strong>N</strong></td>
</tr>
</tbody>
</table>
4 SUMMARY AND CONCLUSIONS

Over the course of this project, NETL researchers studied a number of aspects related to the use of 3D printing technologies in N95 respirator development. Because of supply shortages due to COVID-19, there is a need for rapid development of PPE which can protect front line workers, first responders, and the general public. While there are existing 3D printable designs for respirators available online, the credibility, quality, and rigor of design are largely unknown. Furthermore, few, if any, have undergone the type of quantitative testing necessary to gain a clear understanding of their efficacy in protecting against sub-micron droplets. This project attempted to address these issues, by utilizing the knowledge, experience, and capabilities of the national laboratory system to design, manufacture, and test N95 respirator prototypes.

Throughout the project, communication between the national labs was facilitated through the establishment of a mask/respirator working group, led by NETL. Participating labs included NETL, SNL, NREL, ANL, and Ames Lab. Through weekly meetings and file sharing through a dedicated NETL Energy Data Exchange (EDX) drive workspace, ideas and information were shared among researchers. Special thanks goes to ORNL and SNL for their contributions to the group, sharing early respirator designs and testing results, enabling others to more rapidly advance their projects.

Ultimately, the knowledge generated is expected to be of use to the ‘maker’ community, universities, and commercial manufacturers, to provide an understanding of the challenges, limitations, and opportunities associated with the use of 3D printing technologies for N95 respirator development. While there are a number of 3D printing technologies available, NETL researchers utilized FDM printers in a majority of the work, which is by far the most popular and widely available. FDM parts have reasonably good surface quality and accuracy, however, may suffer from a level of porosity, even at the most dense build settings. For this reason, some published 3D printable mask designs [15] specifically call out a requirement for nylon vat photopolymerization or similar print technology.

With this in mind, care must be taken in how FDM (or polyjet) printed parts are utilized. For the sole purpose of fit testing, these materials can be utilized without issue, provided they are being handled and fitted to the same individual. Sharing of FDM or polyjet printed parts among test subjects during the pandemic may be of concern due to an inability to fully decontaminate as a result of the porous structure. This assertion was not tested quantitatively as part of this project; however researchers feel it is best practice and consistent with the non-reusable nature of the N95 filter media itself.

The use of FDM or polyjet printed parts for testing applications is more complicated. When the parts are solely comprised of thick, flat surfaces and the most dense build settings are used (ex. the filter tray or cap in Fig. 16), droplet transmission through the part structure seems unlikely. However, thin, curved geometries can exhibit significant and/or noticeable porosity that precludes their use in a filtration application. Because no quantitative testing of flow or droplet transmission through printed parts was conducted, at this time it is recommended that FDM or polyjet printed parts not be used in real-world applications.

However, prototyping and development of real-world usable parts is still possible in
PROTOTYPING OF N95 RESPIRATORS USING ADDITIVE MANUFACTURING

conjunction with FDM and/or polyjet 3D printing technologies through the use of secondary manufacturing processes. While not suitable for high-pressure commercial techniques such as injection molding, ambient temperature and pressure cast molding through the use of two-part pourable materials can be implemented using thin-shelled FDM printed molds. This process was demonstrated for skin-safe silicone face seals and heat resistant polyurethane mask shells; however, a range of other materials are available. A potential downside of such approaches is the raw material cost and the potential for developing air bubbles. The latter can be mitigated by considering vacuum degassing of the materials prior to molding and/or curing at high pressure. In the case of molded parts, 3D printing allows highly complex parts to be produced, however requires careful consideration of the demolding process.

Vacuum forming is another viable technology, where 3D printed mold forms can be implemented. This approach demonstrated production of extremely high-quality surface finish of mask shells in a completely non-porous manner dictated by the raw thermoplastic sheet. However, trimming of the shells and establishing an air-tight connection to the filter tray can be challenging. Furthermore, material thicknesses greater than the ~1-1.5 mm utilized during the project are suggested for improved rigidity.

While OSHA testing results were far from desired, they highlight several key points related to the design. For one, the fit and sizing of the mask relative to the user’s face is of utmost importance. A major goal here was a slim and lightweight mask design, relative to commercial 3M, MSA, or Honeywell designs. As a result, the initial prototype was developed with a specific face size/shape in mind (slim/tall), which happened to differ from that of the tester. It is expected that if multiple sizes had been available, testing results would have been significantly improved. Next, it was found that the strap attachment interface had a significant influence on ensuring even pressure around the perimeter of the face seal. Further revisions are likely to have improved fit and retention. Finally, an alternative configuration in which a majority of the mask is deformable may be preferred. This would be a similar approach to commercial offerings and may have enabled improved fit on a variety of face shapes. However, the only deformable material on hand (skin safe silicone) did not have sufficient rigidity as to form a complete shell from. This is particularly relevant with respect to the community driven 3D printed designs that have become common-place in response to the COVID-19.

5 NEXT STEPS

Using what was learned over the course of this project, a number of additional revisions could be made which are likely to significantly improve the performance of the respirator. Additionally, more detailed characterization of several aspects would be desired. First, it would be desired to test the existing design on a more appropriate face type (tall/slim). If results are significantly improved, it may be considered to simply translate the existing design to alternate NIH headforms and verify performance on different face types.

Next, a higher durometers skin safe rubber would be identified to attempt a revised design in which the shell and face seal are a single component. This may offer improved fit by allowing a more substantial seal geometry to be created while retaining sufficient rigidity (the Eco Flex silicone used was very soft and pliable, making it difficult to create unsupported features).
This would require separate, modular filter connections; however, the existing design could likely be utilized. In conjunction with this, would be an alternative strap connection geometry, which more evenly distributes force around the mask perimeter. Even if continuing with a rigid shell, this is one area which would still be addressed.

Finally, improved characterization of leak points would be performed. Two areas in specific would be targeted: 1) ensuring that the filter holders sufficiently clamp the N95 fabric that no particles can bypass the filter, and 2) ensuring that the filter connection points are unable to leak. It is believed that the current design is such that both of these areas are leak free, however quantifying this will ensure revisions are being made to the most critical areas (ex. the face seal geometry). By taking these steps, the next revision is likely to have significantly improved performance. After verifying this through quantitative testing, feedback from end users would be sought, for example front line medical workers and first responders. From here, further revisions could be made if needed, and transfer of the design to commercial partners could be considered.

ACKNOWLEDGEMENTS
This research was funded under DOE NETL Field Work Proposal NETL-RIC-001-2020-011 (Manufacturing Science for Innovations in Medical Supply Chains).

REFERENCES


ncov/hcp/non-us-settings/overview/index.html.


**Appendix A – Portacount Test Results**

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<thead>
<tr>
<th>Exercise</th>
<th>Duration (sec)</th>
<th>Fit Factor</th>
<th>Pass</th>
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</thead>
<tbody>
<tr>
<td>Normal Breathing</td>
<td>64</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Deep Breathing</td>
<td>64</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Side to Side</td>
<td>64</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Up and Down</td>
<td>64</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Talking</td>
<td>54</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Grimace</td>
<td>15</td>
<td>Excl</td>
<td>N</td>
</tr>
<tr>
<td>Bending Over</td>
<td>64</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td>Normal Breathing</td>
<td>54</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Overall FF</td>
<td></td>
<td>3</td>
<td>N</td>
</tr>
</tbody>
</table>

**Respirator Fit Test Card**

**Name:** DON FERGUSON  
**ID:** 2773  
**Test Date:** 11/24/2020  
**Next Test Date:** 11/24/2021

**Respirator**

- **Mfg:** NELT
- **Model:** BLUE PRINT
- **Style:** BLUE PRINTED
- **Size:** medium
- **Operator:** LINGER

**Results**

- **Overall FF:** 3
- **FF Pass Level:** 100
- **Pass:** N

**Protocol:** OSHA 29CFR1910.134  
**Fit Test Method:** ONFT using TSI Portacount  
***Your company contact information here***
## FIT TEST REPORT

**11/24/2020**

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**LOCATION**

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**RESPIRATOR**

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**EXERCISE**

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**OVERALL FF**

| OVERALL FF | 90 | N |

**FIT TEST OPERATOR**

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**NAME**

<table>
<thead>
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**Note:**

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### Respirator Fit Test Card

**Name:** DON FERGUSON  
**ID:** 2773  
**Test Date:** 11/24/2020  
**Next Test Date:** 11/24/2021  

**Respirator**

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**Results**

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<tr>
<td>Pass</td>
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</tr>
<tr>
<td>Operator</td>
<td>LINGER</td>
</tr>
</tbody>
</table>

**Protocol:** OSHA 29CFR1910.134  
**Fit Test Method:** ONET using TSI PortaCount  
*** Your company contact information here ***
## Fit Test Report

**ID Number:** 2773  
**Last Name:** FERGUSON  
**First Name:** DON  
**Company:** DOE  
**Location:** CUSTOM4  
**Test Date:** 1/29/2021 10:07  
**DUE Date:** 1/29/2022  
**Respirator:** NETL BLACK PRINTED HALF MASK 2 HALF MASK 100  
**Manufacturer:** NETL  
**Model:** BLACK PRINTED HALF MASK 2  
**Mask Style:** HALF MASK  
**Mask Size:** medium  
**Port Acount S/N:** 8038123912  
**N95 Companion:** N  
**Protocol:** OSHA 29CFR1910.134  
**Pass Level:** 100  
**Approval:** EFFICIENCY<99%  
**False**

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Duration (sec.)</th>
<th>Fit Factor</th>
<th>PASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Breathing</td>
<td>64</td>
<td>5</td>
<td>N</td>
</tr>
<tr>
<td>Deep Breathing</td>
<td>64</td>
<td>4</td>
<td>N</td>
</tr>
<tr>
<td>Head Side to Side</td>
<td>64</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Head Up and Down</td>
<td>64</td>
<td>6</td>
<td>N</td>
</tr>
<tr>
<td>Talking</td>
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<td>6</td>
<td>N</td>
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<tr>
<td>Grimace</td>
<td>15</td>
<td></td>
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<tr>
<td>Bending Over</td>
<td>64</td>
<td>2</td>
<td>N</td>
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<tr>
<td>Normal Breathing</td>
<td>64</td>
<td>22</td>
<td>N</td>
</tr>
<tr>
<td>Overall FF</td>
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<td>4</td>
<td>N</td>
</tr>
</tbody>
</table>

**Fit Test Operator:** LINGER

**Name:** DON FERGUSON  
**Date:**

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**Respirator Fit Test Card**

**Name:** DON FERGUSON  
**Test Date:** 1/29/2021  
**ID:** 2773  
**Next Test Date:** 1/29/2022

**Respirator**

- **Mfg:** NETL  
- **Model:** BLACK PRINTED  
- **Style:** HALF MASK  
- **Size:** medium  
- **Overall FF:** 4  
- **FF Pass Level:** 100  
- **Pass:** N  
- **Operator:** LINGER

**Results**

- **Protocol:** OSHA 29CFR1910.134  
- **Fit Test Method:** ONFT using Till PortaCount  
- **Your company contact information here:**